

# Photon-assisted spin transport in a two-dimensional electron gas

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(Dated: February 1, 2008)

We study spin-dependent transport in a two-dimensional electron gas subject to an external step-like potential  $V(x)$  and irradiated by an electromagnetic field (EF). In the absence of EF the electronic spectrum splits into spin sub-bands originating from the "Rashba" spin-orbit coupling. We show that the resonant interaction of propagating electrons with the component EF parallel to the barrier induces a *non-equilibrium dynamic gap* ( $2\Delta_R$ ) between the spin sub-bands. Existence of this gap results in coherent spin-flip processes that lead to a spin-polarized current and a large magnetoresistance, i.e the spin valve effect. These effects may be used for controlling spin transport in semiconducting nanostructures, e.g. spin transistors, spin-blockade devices etc. , by variation of the intensity  $S$  and frequency  $\omega$  of the external radiation.

PACS numbers: 85.75.-d, 72.25.-b, 05.60.Gg

## I. INTRODUCTION

Study of a spin-dependent transport in diverse mesoscopic systems, e.g. junctions with ferromagnetic layers, magnetic semiconductors, and low-dimensional semiconducting nanostructures remains one of the most popular topics during the last decades<sup>1,2,3</sup>. Such systems display fascinating spin-dependent phenomena, e.g. giant magnetoresistance (the spin valve effect)<sup>2,3</sup>, spin-polarized current<sup>4,5,6</sup>, and spin-transistor effects<sup>7,8,9</sup>, just to name a few. Application of these effects has resulted in the emerging of new technologies based on using the electron spin (so-called "spintronics").

An interesting and important example of how the spin-dependent transport can be realized experimentally is a two-dimensional electron gas (2DEG) formed in a semiconducting quantum well. In this particular system a strong spin-orbit interaction is induced by inhomogeneous electric field in the direction perpendicular to the 2DEG plane, which is usually referred to as the Rashba effect<sup>10</sup>. The Rashba spin-orbit interaction results in a splitting of the 2DEG electronic spectrum  $\epsilon(p)$

$$\epsilon_{\pm}(p) = \frac{p^2}{2m} \pm \alpha|\mathbf{p}|, \quad (1)$$

where  $\mathbf{p} = \{p_x, p_y\}$  is the quasi-particle momentum,  $m$  is the effective mass, and  $\alpha$  is the strength of the spin-orbit interaction. The signs  $\pm$  in Eq. (1) correspond to different electron spin projections.

Dynamics of the spins in the presence of the spin-orbit interaction is characterized by a spin precession around the direction perpendicular to the momentum  $\mathbf{p}$  (in the 2DEG plane). This precession is the basis for diverse proposals for spin transistors with the use of *homogeneous* 2DEG<sup>7,8,9</sup>. An additional control of a spin-dependent transport can be obtained by variation of the spin precession axis. This goal may be achieved by creating artificially a coordinate dependent potential  $V(x)$ <sup>6</sup>. Such a potential can be produced by using a split-gate technique or cleaved edge fabrication method<sup>11</sup>.

In the static case, as no time-dependent fields are applied, the precession frequency and the corresponding splitting between the spin sub-bands are determined by both the transverse quantization of the momentum  $\mathbf{p}$ , and a total change of the potential  $V(x)$ <sup>6</sup>. Such a setup might allow one to produce the spin-polarized current for quasi-particles with nonzero values of the transverse momentum. However, to observe this effect a small value of  $\epsilon_0 - V \simeq m\alpha^2$  proportional to the small parameter  $\alpha^2$  has to be used ( $\epsilon_0$  is the Fermi energy)<sup>6</sup>. Moreover, the quasi-particles propagating in the direction perpendicular to the barrier are not spin-polarized.

In this paper we suggest a new method of producing spin-polarized current using a similar structure with the 2DEG and a step-like potential  $V(x)$ . However, in addition to the previous set up, we assume that the system is irradiated by an external electromagnetic field (EF). We demonstrate that in this situation the ballistic transport of the quasi-particles moving perpendicular to the barrier can be extremely sensitive to the time-dependent perturbation provided certain resonant conditions are met. Notice here that although our analysis is applied directly to the Rashba type of a spin-orbit interaction, similar effects can be obtained also in systems with a bulk asymmetry displaying Dresselhaus type of a spin-orbit interaction<sup>12</sup>

## II. MODEL AND QUALITATIVE ANALYSIS

To be specific, we consider 2DEG subject to an external potential  $V(x)$ , and in the presence of an EF applied in the transverse direction parallel to the potential barrier. The system is represented in Fig. 1. We stress here that, although the EF need not be linearly polarized, only the component of EF parallel to the interface ( $y$ -direction) leads to the resonant interaction between the spin sub-bands.

The resonance condition can be written as  $\hbar\omega = 2\alpha|\mathbf{p}(x)|$ , where  $\omega$  is the frequency of EF, and  $\mathbf{p}(x)$  is the coordinate dependent classical momentum of the

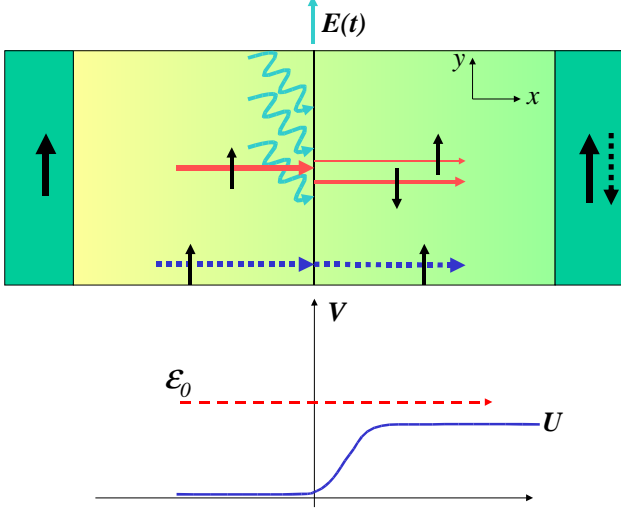


FIG. 1: (color online) Transport in a 2D electron gas with spin-polarized electrodes. The ferromagnetic (anti-ferromagnetic) configuration of the leads is shown. The 2D electron gas interacts with an external potential  $V(x)$  and is irradiated by electromagnetic field (EF). The dashed (solid) lines display spin transfer in the absence (presence) of EF.

quasi-particles. Such a resonant interaction leads to forming a *non-equilibrium dynamic gap* ( $2\Delta_R$ ) between the spin sub-bands. The quantity  $\Delta_R/\hbar$  has the same meaning as the famous Rabi frequency for microwave induced quantum coherent oscillations between two energy levels<sup>14</sup> (these energy levels are  $\frac{|\mathbf{p}(x)|^2}{2m} + \alpha|\mathbf{p}(x)|$  and  $\frac{|\mathbf{p}(x)|^2}{2m} - \alpha|\mathbf{p}(x)|$  in our case). The value of the gap depends strongly on the intensity  $S$  and frequency  $\omega$  of the external radiation.

The dynamic gap induces coherent spin-flip processes and manifests itself in generating a spin polarization of the current. This may also lead to a strong suppression of the conductivity  $G$  of 2DEG with spin-polarized (ferromagnetic) leads, i.e. the spin-valve effect (see Fig. 1).

### III. FLOQUET EIGENVALUES OF THE PROBLEM

We start our analysis writing a time and coordinate dependent two spin-band Hamiltonian  $\hat{H}(t)$  in the external EF

$$\hat{H}(t) = \frac{[\hat{\mathbf{p}} - \frac{e}{c}\mathbf{A}]^2}{2m} + \alpha \left[ \hat{\sigma} \times \left\{ \hat{\mathbf{p}} - \frac{e}{c}\mathbf{A}(t) \right\} \right]_z + V(x), \quad (2)$$

where the  $\hat{\sigma} = \{\hat{\sigma}_x, \hat{\sigma}_y\}$  are the standard Pauli matrices. The electromagnetic wave is represented by the  $y$ -component of the vector-potential as  $A_y = (Ec/\omega) \cos(\omega t)$ , where  $E = \sqrt{4\pi S/c}$  is the amplitude of the electric field.

Next, we take into account the *resonant interaction* between the EF and propagating quasi-particles, only.

Therefore, we neglect a weak non-resonant interaction of quasi-particles with EF that is e.g. due to the presence of a time-dependent vector-potential  $\mathbf{A}$  in the first term of the Hamiltonian (2). In this case the time-dependent problem described by the Hamiltonian (2) is reduced to a stationary problem by switching to a rotating frame with the following unitary transformation of the two component wave functions

$$\hat{U}_n = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -\exp(-i\hat{\theta}) & \exp(-i\hat{\theta}) \end{pmatrix} \exp \left[ i\omega t \left( n - \frac{\hat{\sigma}_z + 1}{2} \right) \right], \quad (3)$$

where  $\hat{\theta} = \tan^{-1}(\hat{p}_x/\hat{p}_y)$  and  $\hat{p}_x, \hat{p}_y$  are the components of momentum operators perpendicular and parallel to the interface, respectively. A similar procedure has been used to analyze the transport in a graphene layer in the presence of EF<sup>13</sup> but spin degrees of freedom were irrelevant in that consideration.

The transformation, Eq. (3), changes the initial Hamiltonian to  $\hat{H}'_{eff} = \hat{U}_n^\dagger \hat{H} \hat{U}_n - i\hbar \hat{U}_n^\dagger \dot{\hat{U}}_n$ . The latter contains, in general, both static and proportional to  $\exp(\pm 2i\omega t)$  parts. However, like for the two level systems<sup>14</sup>, only the static part of  $\hat{H}'_{eff}$  is important near the resonance, and it can be written as

$$\begin{aligned} \hat{H}'_{eff} = & \frac{|\hat{\mathbf{p}}|^2}{2m} + V(x) + \\ & + \begin{pmatrix} \hbar(n-1)\omega + \alpha|\hat{\mathbf{p}}| & \frac{eE\alpha}{2\omega} \\ \frac{eE\alpha}{2\omega} & \hbar n\omega - \alpha|\hat{\mathbf{p}}| \end{pmatrix}, \end{aligned} \quad (4)$$

where  $|\hat{\mathbf{p}}| = \sqrt{\hat{p}_x^2 + \hat{p}_y^2}$ .

Neglecting the oscillating part of the Hamiltonian  $\hat{H}'_{eff}$  corresponds to a rotation wave approximation (RWA)<sup>14</sup>. The RWA is valid in the most interesting regime of the resonant interaction between the EF and propagating quasi-particles when

$$\hbar\omega \simeq 2\alpha|\mathbf{p}(x)| \quad (5)$$

We also assume that the amplitude of the external microwave radiation is comparatively small,  $eE\alpha/\hbar \ll \omega^2$ .

The Eq. (4) shows that the EF results in the appearance of off-diagonal elements in the operator  $\hat{H}'_{eff}$ . In the absence of the coordinate dependent potential, i.e.  $V(x) = 0$ , the eigenvalues  $\tilde{\epsilon}(p)$  of  $\hat{H}'_{eff}$  give the sets of bands of quasi-energies (the Floquet eigenvalues<sup>14</sup>):

$$\tilde{\epsilon}_{n,\pm}(p) = \frac{\mathbf{p}^2(x)}{2m} + (n - \frac{1}{2})\hbar\omega \pm \sqrt{(\alpha|\mathbf{p}(x)| - \frac{\hbar\omega}{2})^2 + \Delta_R^2} \quad (6)$$

where

$$2\Delta_R = (e\alpha/\omega)\sqrt{4\pi S/c} \quad (7)$$

is the EF induced non-equilibrium gap and  $n$  are integer numbers  $n = 0, \pm 1, \pm 2, \dots$ . It is well known<sup>14</sup> that, in

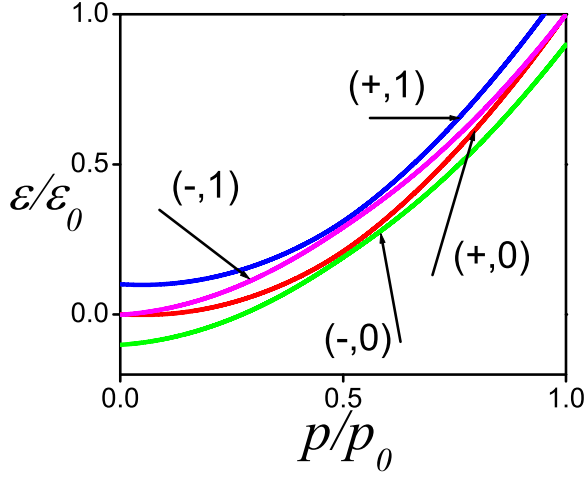


FIG. 2: (color online) The bands of Floquet eigenvalues for  $n = 0, 1$  are shown. Each band is characterized by a sign in the Eq. (6) and integer number  $n$ . The parameters  $\hbar\omega = \alpha p_0 = 0.1\epsilon_0$ ,  $\Delta_R = 0.01\epsilon_0$  were chosen. The momentum  $p_0$  is defined as  $\epsilon_0 = p_0^2/(2m)$ .

the presence of periodic time-dependent perturbations, the bands of the Floquet eigenvalues replace the quasi-particle spectrum, Eq. (1). The typical bands of Floquet eigenvalues are shown in Fig. 2.

#### IV. PHOTON ASSISTED SPIN DYNAMICS: QUASI-CLASSICAL DESCRIPTION

Next, we analyze the spin-dependent transmission of quasi-particles  $P_{\uparrow(\downarrow),\uparrow(\downarrow)}$  through the potential barrier  $V(x)$  formed in the 2DEG. Here, the  $\uparrow$  ( $\downarrow$ ) corresponds to positive (negative) values of a spin projection on the  $y$ -axis. To obtain the analytical solution we use the quasi-classical approximation that can be quite realistic in the presence of a smooth potential created electrostatically. The classical phase trajectories  $p(x)$  of the Hamiltonian  $\hat{H}_{eff}$  are determined by the conservation of the sum of the potential energy  $V(x)$  and the quasi-energy  $\tilde{\epsilon}_{n,\pm}(p)$  as

$$V(x) + \tilde{\epsilon}_{n,\pm}(p) = \epsilon_0 \quad (8)$$

Using Eqs. (6) and (8) for  $n = 0, 1$  we obtain four spin-dependent phase trajectories characterized by a sign in the Eq. (6) and integer number  $n$ . A further progress can be made by choosing a specific model for the electrostatic potential formed in 2DEG ( $d$  is the characteristic width of the potential)<sup>15</sup>

$$V(x) = \begin{cases} 0, & x < 0 \\ Fx, & 0 < x < d \\ U = Fd, & x > d \end{cases} \quad (9)$$

Since the influence of EF is diminished for quasi-particles possessing a large transverse momentum  $p_y \simeq p_x$ , we

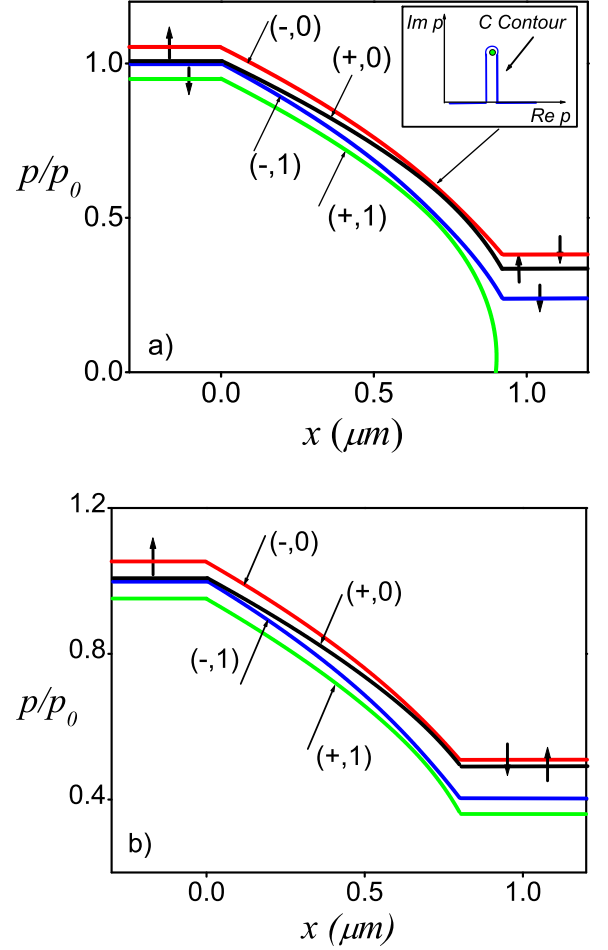


FIG. 3: (color online) Spin-dependent phase trajectories  $p(x)$  of the Hamiltonian  $\hat{H}_{eff}$  for two cases: a) spin-polarized current is established, the potential barrier height  $U = 0.92\epsilon_0$  was used; b) the magnetoresistance effect is realized, the potential barrier height  $U = 0.8\epsilon_0$  was used. Insert shows the contour of integration in the complex plane used when calculating the "tunneling" process between adjacent phase trajectories. The values of parameters  $\hbar\omega = \alpha p_0 = 0.1\epsilon_0$ ,  $d = 1\mu m$  and  $\Delta_R = 0.01\epsilon_0$  were chosen.

just consider a one-dimensional transport with  $p_x \gg p_y$ . The typical phase trajectories for the potential  $V(x)$ , Eq. (9), are shown in Fig. 3.

As the quasi-particles approach the barrier, the momentum  $p_x$  decreases, the resonance condition is satisfied sufficiently close to the junction, and, therefore, the interaction with the EF opens the gap  $2\Delta_R$  between neighboring trajectories. In this case the propagation along the phase trajectories corresponds to the *coherent spin-flip processes*, and the spin conservation is possible only due to the switching ("tunneling") between adjacent trajectories (see Fig. 3). In the regime of strong induced spin-flip processes, the probability of such dynamical tunneling  $P_{tun}$  is small and  $P_{tun}$  is obtained by a shift of the integration contour  $C$  in the complex  $p$  plane around the branch point ( $\tilde{p} = \hbar\omega/(2\alpha) + i\Delta_R/v\alpha$ )<sup>13,15,16</sup> (see, insert

in Fig. 3a) as

$$P_{tun} = \left| \exp \left\{ i \frac{2}{\hbar} \int p(x) dx \right\} \right| = \left| \exp \left\{ i \frac{2}{\hbar F} \int_C \tilde{\epsilon}_n(p) dp \right\} \right|, \quad (10)$$

Substituting the expressions for the Floquet eigenvalues, Eq. (6), into Eq.(10), and calculating the integral in Eq. (10) we write the probability of the dynamical tunneling  $P_{tun}$  as

$$P_{tun} \simeq \exp \left[ -\frac{\pi \Delta_R^2}{\hbar \alpha F} \right], \quad (11)$$

where the gap  $2\Delta_R$  should be taken from Eq. (7).

The probability of the spin-flips  $P_{sf}$  is given by the following expression  $P_{sf} = 1 - P_{tun}$ . Therefore, the external radiation of the frequency  $\omega \sim \alpha p_0/\hbar$ , where  $p_0$  is the Fermi momentum, satisfying the resonant condition can induce strong spin-flip processes as  $P_{sf} \simeq 1$ . In the opposite case of a large frequency,  $\omega \geq 2\alpha p_0/\hbar$ , the EF cannot provide the resonant interaction, and the propagation of quasi-particles moving perpendicular to the barrier is not spin-dependent.

## V. DISCUSSION AND CONCLUSIONS

Using Eqs. (8, 10) we see that a spin-polarized current can be created provided potential step  $U$  is sufficiently high, such that  $\epsilon_0 - U < \hbar\omega$ . Indeed, as it is shown in Fig. 3a, the quasi-particles moving along the lower phase trajectory, are reflected from the barrier. Therefore, the probability  $P_{\downarrow,\uparrow} = 0$ . Other spin-dependent probabilities of quasi-particles propagation are  $P_{\uparrow,\uparrow} = P_{\downarrow,\downarrow} = P_{tun}$  that corresponds to the switching between  $(-, 0) \rightarrow (+, 0)$ , and  $(+, 1) \rightarrow (-, 1)$  trajectories (see Fig. 2a). The quasi-particle motion along the upper phase trajectory is characterized by a probability  $P_{\uparrow,\downarrow} = 1 - P_{tun}$ . Therefore, if on the left side of 2DEG the non spin-polarized quasi-particles are induced, the total polarization of transmitted quasi-particles moving perpendicular to the barrier equals

$$|< \sigma_y >| = |-(1 - P_{tun}) + P_{tun} - P_{tun}| = 1 - P_{tun} \quad (12)$$

In experiments, the EF induced spin-flips processes lead also to a large magnetoresistance effect in the conductivity  $G$  of a 2DEG with spin-polarized electrodes (see Fig. 1). We use the simplest setup with the magnetization in the leads directed along the  $y$  axis. In this case, we can neglect the quantum-mechanical interference between the different spin states, and the conductivity  $G$  is determined by the probability of spin-flip processes,  $P_{sf}$ . Moreover, the conductivity depends on the relative directions of magnetization axes in the leads. Thus, in the case of the ferromagnetic configuration of the leads, i.e. when the directions of the magnetization in both the electrodes coincide, the conductivity  $G_{\uparrow,\uparrow} \propto P_{tun}$  is strongly suppressed. On the contrary, in the case of the

anti-ferromagnetic configuration of the leads, i.e. when the directions of magnetization in electrodes are opposite to each other, the conductivity  $G_{\uparrow,\downarrow} \propto (1 - P_{tun})$  is not suppressed. The diverse phase trajectories characterizing the spin dynamics for such a case are shown in Fig. 3b. These results are valid provided the potential barrier is not too high, i.e.  $\hbar\omega < \epsilon_0 - U < \epsilon_0 (\frac{\hbar\omega}{2\alpha p_0})^2$ . Notice here, that in contrast to diverse spin valve devices<sup>2,3</sup> the photon-assisted magnetoresistance displays negative value.

Finally, we address the question of experimental conditions necessary to observe the predicted effects. An experimental setup has to provide a ballistic transport in a 2DEG in order to avoid the incoherent spin-flip processes. In systems with spin-orbit coupling these processes arise due to the presence of randomly distributed impurities (the Dyakonov-Perel spin flip mechanism<sup>18</sup>). Therefore, the elastic scattering of quasi-particles diminishes the obtained effects. Moreover, the elastic scattering and/or all mechanisms leading to the inhomogeneous broadening of the EF can also directly modify the probability of photon-assisted spin-flip processes i.e. the  $P_{tun}$ . This effect demands a separate analysis and goes beyond a scope of this paper. A barrier with the typical width  $d \simeq 1\mu m$  in a 2DEG has to be fabricated. An external radiation containing the component parallel to the barrier of a moderate intensity  $S$  has to be applied. We emphasize that EF need not be linearly polarized. The EF induces the spin-flips processes and corresponding spin-dependent quasi-particle transmission through the barrier in the range of the frequencies of EF  $\omega \simeq \alpha p_0$ . For example in the *InAs*-based heterostructures characterized by a strong spin-orbit coupling<sup>17</sup>, the spin-dependent transport can be controlled by the EF with the frequency  $\simeq 1 THz$ . To observe intensive resonantly induced spin-flip processes, and therefore, a spin-dependent transport one may use the radiation with a moderate intensity  $S > 0.4 W/cm^2$ . In order to obtain a spin-polarized current the barrier has to be rather high:  $\epsilon_0 - U < \hbar\omega \simeq 3meV$ . The magnetoresistance effect can be observed for moderate values of the barrier:  $3meV < \epsilon_0 - U < \epsilon_0/4 \simeq 10meV$ .

In conclusion, we have demonstrated that the resonant radiation of a moderate intensity  $S$  applied to a ballistic 2DEG with the spin-orbit interaction leads to a spin-polarized current and/or a strong magnetoresistance effect in the conductivity of a 2DEG with ferromagnetic leads. These effects occur due to formation of a non-equilibrium dynamic gap between spin-subbands in the quasi-particle spectrum as the resonant condition  $\hbar\omega = 2\alpha|\mathbf{p}|$  is satisfied. In the presence of spatially dependent potential formed in a 2DEG, such a resonance condition is satisfied somewhere in the vicinity of the barrier. The presence of the gap induces intensive coherent spin-flips processes on the barrier. In order to conserve the spin value the quasi-particles have to "tunnel" between the quasi-classical trajectories. The value of the gap and, therefore, this specific type of the tunnelling is controlled by variation of the intensity  $S$  and frequency  $\omega$

of the external radiation. We hope that the predicted effect will find its applications to non-equilibrium (photon-assisted) spintronics devices based on a 2DEG.

We would like to thank P. Silvestrov, A. Kadigrobov and S. Syzranov for useful discussions and acknowledge the financial support by SFB 491.

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